Evaluation of the Hydraulic Conductivity of Compacted Laterite-Metakaolin Mixtures for Solid Waste Leachate Containment

*Sa'eed Y. Umar and Augustine U. Elinwa
Department of Civil Engineering, Abubakar Tafawa Balewa University, Bauchi, Nigeria
umarsyusuf@yahoo.com | auelinwa@gmail.com

Submitted: 15-FEB-2020; Reviewed: 12-MAR-2020; Accepted: 28-MAR-2020

Abstract- This paper presents the results of a study conducted to investigate the benefits of using metakaolin (MK) with laterite as liner material for containment of municipal solid waste (MSW)**.** Laboratory tests were conducted on laterite specimens treated with MK at concentrations of 0 **-** 20 % by weight of the soil and compacted using four types of compaction energies. Hydraulic conductivity was determined based on permeation of the compacted laterite - MK mixtures with deionized water (DW) and municipal solid waste leachate (MSWL), respectively. Deionized water was the reference permeant fluid. The results showed that hydraulic conductivity generally decreased with increase in the percentage addition of MK to the soil. From an economic and sustainability point of view, it has been found from the results that 5 % MK can be added to soil and compacted at moulding water content of 14.1 % using the West African Standard (WAS) compaction energy to achieve the regulatory hydraulic conductivity of less than or equal to 1×10^{-9} m/s for compacted soil liner. The natural logarithm of the hydraulic conductivity experimental results was computed and used to develop regression equations for estimating hydraulic conductivity given MK contents and compaction energies. The results of the two-way analysis of variance (ANOVA) test carried out at 5 % level of significance showed that calculated F-statistics are statistically significant and the measured values of hydraulic conductivity compare well with the predicted values. The developed models can therefore be used to give good estimates of hydraulic conductivity of soils having similar properties with the laterite investigated in this study. Therefore, the developed models can be used to give good estimates of hydraulic conductivity of soils having similar properties with the laterite investigated in this study.

Keywords – Deionized water, Hydraulic conductivity, Leachate, Metakaolin, Municipal solid waste.

1 Introduction

One advantage of compacted clay soil is low hydraulic conductivity making the soil suitable as a liner material for containment of municipal solid waste. In spite of this advantage, compacted clay soils could exhibit high shrinkage and high expansion potential causing instability problems when used as material for containment of MSW (Mitchell, 1993; Kleppe & Oslon, 1995). In view of the high expansion potentials of clay soils, it becomes necessary to explore the suitability of soils having low swelling potentials for construction of hydraulic barrier system for containment of MSW.

Laterites are characterized by low swell potential, low shrinkage and high density when compacted at optimum water content. Previous studies on laterites showed that some of their properties can be improved upon by using materials such as blast furnace slag, iron ore waste, tincal ore waste, fly ash, waste wood ash, mine tailings, rice husk ash, coal waste, bagasse ash, and sugar cane straw (Kula *et al.*, 2002; Osinubi & Eberemu, 2009; Ramesh *et al.*, 2012; Hamdi and Srasra, 2013; Roy, 2013; Etim, 2015; Oluremi, 2015; Umar *et al.*, 2015; Modarres & Nosoudy, 2015; Umar *et al*, 2016). Several research groups have reported that using alternative supplementary cementitious materials (SCMs) to upgrade the properties of soils could reduce construction cost and enhance the performance of hydraulic barrier systems (Yeheyis *et al.*, 2010; Ilić *et al.*, 2010). Though laterites have been treated with different types of SCMs within the tropical and sub-tropical regions, little research has been undertaken to assess the improvement metakaolin (MK) can make on the hydraulic conductivity of compacted laterite.

*Corresponding author

The advantages of using MK as replacement material for ordinary Portland cement are not only improvement of soil performance but also the environmental benefits in terms of reduction of carbon dioxide (CO_2) emitted from the production of ordinary Portland cement. Previous studies in the addition of MK to soil show improvement in compressive strength, dry density and hydraulic characteristics of soilcrete mixtures (Dinar *et al*, 2013; Kolovos *et al.*, 2013). Earlier, Bradshaw *et al.* (2005) quoted by Kolovos *et al.* (2013) reported that the use of SCMs to replace OPC in soilcrete production is expected to reduce construction costs as well as CO_2 emissions greatly.

This study explores the potentials of using MK to improve the properties of laterite to be used as liner material in hydraulic barrier system for containment of MSW. Minitab 16.1 statistical software was used to develop regression equations for predicting hydraulic conductivity of the laterite - MK mixtures compacted using four methods of compaction.

2 Materials

2.1 Laterite

The laterite used in this study was sourced from Bauchi, Bauchi State, Nigeria using the method of disturbed sampling. Tests for the characterization of the laterite investigated in this study were conducted in accordance with BS 1377 (1990). In order to determine the proportion of fine materials in the laterite, 200 g of the soil was soaked overnight for the wet sieving. The sample was thoroughly washed using the US No. 200 sieve (75 µm aperture). The particles passing the 75 µm sieve size was used for the hydrometer analysis with sodium hexametaphosphate as the dispersant. Particles retain on the sieve was placed in the oven and dried at 105°C overnight before dry sieving was done to obtain the particle size distribution. The chemical compositions of the laterite was analysed using the x-ray fluorescence (XRF) spectroscopy method.

2.2 METAKAOLIN

The raw material used for the production of MK is kaolin. The kaolin used in this study was sourced from Alkaleri Local Government Area in Bauchi State, Nigeria. To obtain the MK used in this study, kaolin was heated to a temperature of 650^{o}C in a kiln developed by the Department of Industrial Design, Abubakar Tafawa Balewa University, Bauchi. The chemical properties of the resulting MK were analyzed using the XRF spectroscopy method.

2.3 MUNICIPAL SOLID WASTE

The municipal solid waste (MSW) used in this study was sourced from an active unlined landfill site (refuse dump) in Yelwa Market, Bauchi, Nigeria. The MSW leachate was obtained using nitric acid (HNO_3) as the chelating agent. The chemical properties of the MSW leachate were determined by means of the Atomic Absorption Spectrophotometer (AAS Buck Model 210 VGP) and the organic content was analyzed by measuring the 5 - day biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD).

3 METHODOLOGY

3.1 COMPACTION

Four methods of compaction namely: Reduced British Standard Light (reduced Proctor, RBSL), British Standard Light (standard Proctor, BSL), West African Standard (intermediate, WAS) and British Standard Heavy (modified Proctor, BSH) were used. The RBSL compaction method is equivalent to 331.09 kj/m^3 of compaction energy, or 55.56 % of ASTM D 698-12 while the WAS compaction method is equivalent to 993.29 kj/m^3 of compaction energy, or 166.67 % of ASTM D 698-12. The characteristics of the compaction methods used are presented in Table 1.

The laterite was allowed to dry at room temperature and pulverized to sizes small enough to pass 4.76 mm sieve aperture. A total of 20 mixes were prepared by adding 0 - 20 % MK by weight of the soil. Moulding moisture contents used for preparation of the specimens ranged from 10 - 20 %. The control mix containing 0 % MK was labeled C_0 - 0MK, and the remaining four mixes were labeled C_1 - 5MK, C_2 - 10MK, C_3 - 15MK and C_4 - 20MK reflecting the levels of addition of MK to the soil by weight. For each percentage addition of MK, three specimens were prepared and compacted. The average of optimum moisture contents (w_{opt}) and maximum dry density (ϱ_{dmax}) were determined.

3.2 HYDRAULIC CONDUCTIVITY

The hydraulic conductivity tests were conducted in a rigid wall compaction mould permeameter conforming to ASTM D 5084-10. The soil sample for this test was air dried under laboratory condition and pulverized to sizes small enough to pass 4.76 mm sieve aperture. Three kilograms (3 kg) of the soil was measured and compacted at water contents of +2 % w_{opt} in a 1000 cm^3 mould. US EPA (1989) recommended that w_{opt} of soils to be used as liner material can be increased by 2 % before compaction.

As was the case for compaction tests, five mixes were prepared at MK contents ranging from 0 - 20 % by weight of the soil and compacted using the four energy levels illustrated in Table 1. The control mix containing 0 % MK was labeled H_0 - 0MK and the remaining four mixes containing MK were labeled H_1 - 5MK, H_2 - 10MK, H_3 - 15MK and H_4 - 20MK reflecting the levels of addition of MK to the soil. A total of 120 specimens were prepared for hydraulic conductivity measurements using deionized water (DW) and municipal solid waste leachate (MSWL) as the permeant fluids, respectively. Sixty specimens were permeated with deionized water and the remaining 60 specimens with MSWL. For each percentage addition of MK, three specimens were prepared and compacted. The hydraulic conductivity (k) was computed using equation (1).

$$k = 2.303 \frac{aL}{100At} \log_{10} \frac{y_1}{y_2}, \qquad (1)$$

Where: k is the hydraulic conductivity (m/s), a is the area of standpipe tube (m^2), L is the specimen disc thickness along the flow path (m), A is the specimen disc cross-sectional area (m^2), t is the elapsed time over which the flow occurs (s), y_1 is the height of water above datum in standpipe at time t_1 (m) and y_2 is the height of water above datum in standpipe at time t_2 (m).

4 DISCUSSION OF RESULTS

4.1 CHARACTERIZATION OF MATERIALS

Laterite - The particle size distribution curve of the laterite is shown in Fig. 1 and the physical characteristics of the laterite are summarized in Table 2. The laterite is classified as A-6(29) in accordance with the American Association of State Highway and Transportation Officials (AASHTO) M145-12 classification system and CL in accordance with the American Society for Testing and Materials classification system ASTM D2478-11.

Table 1. Characteristics of compaction methods used

Compaction method	Volume of mould (cm^3)	Weight of rammer (kg)	Height of fall (cm)	Number of layers	Number of blows	Work done (kJ/m^3)
RBSL	1000	2.5	30.48	3	15	(331.088)[a]
BSL	1000	2.5	30.48	3	27	595.958
WAS	1000	4.5	45.75	5	10	(993.293)[b]
BSH	1000	4.5	45.72	5	27	2681.809

a. RBSL: 332.088 kJ/m^3 of compaction energy, or 55.56 % of ASTM D 698 – 12,
b. WAS : 993.293 kJ/m^3 of compaction energy, or 166.67 % of ASTM D 698 – 12

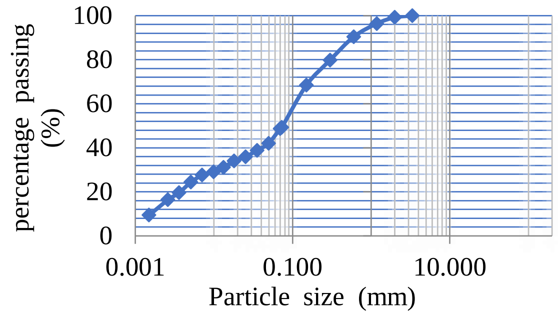

Fig. 1: Particle size distribution curve of the laterite

Table 2. Physical characteristics of the laterite.

Property	Value
Percentage Passing BS No. 200 Sieve	62
Natural Moisture Content (%)	5
Liquid Limit (%)	38
Plastic Limit (%)	22
Plasticity Index (%)	16
Specific gravity	2.4
Plasticity Product	143
Color	Reddish Brown
AASHTO Classification	A-6(29)
USCS Classification	CL
Silica Sesquioxide Ratio	1.21

Metakaolin - The chemical compositions of MK by total weight is presented in Table 3. The MK used has a moisture content of 0.18 %, specific gravity of 2.6, bulk density of 0.7 Mg/m^3, pH of 7.0 and conforms to ASTM C618-15 Type F designation.

Table 3. Chemical compositions of laterite and metakaolin (% by total weight).

Chemical composition	Laterite	Metakaolin
Al_2O_3	12.50	34.50
SiO_2	44.70	53.70
K_2O	8.10	0.93
CaO	2.30	0.51
TiO_2	2.20	5.97
V_2O_3	0.10	0.23
MnO	0.20	0.06
Fe_2O_3	24.40	3.84
CuO	0.10	0.03
ZnO	0.10	0.01
Au_2O_3	3.60	-
ReO	0.50	-
UO_2	0.40	-
Cr_2O_3 (%)	-	0.06
NiO (%)	-	0.07
Ga_2O (%)	-	0.09
Total	100.00	100.00

Leachate - The chemical and biochemical characteristics of the MSW leachate are summarized in Table 4. The leachate sample has a pH value of 7.8, BOD_5 of 39.3 mg/l, COD of 136.04 mg/l and the ratio of BOD_5/COD of 0.29. According to Bhalla et al (2013), BOD_5/COD ratio describes the degree of biodegradation of leachate and gives information on the age of a landfill. Low BOD_5/COD ratio of 0.29 shows the presence of high concentration of non-biodegradable organic compounds in the leachate. According to Amokrane *et al.* (1997), high ratio of BOD_5/COD of 0.5 - 0.7 however, indicate large amounts of biodegradable organic matter and is typical of leachate in the acidogenic phase. Calcium (Ca) is the predominant metal in the leachate (373mg/l) followed by K (120 mg/l) while Pb and Cd (0.02 mg/l) were the lowest. Low heavy metals concentration is attributable to the alkaline nature of the leachate.

Table 4. Chemical and biochemical characteristics of the MSW leachate

Parameter	Concentration
pH	7.8
BOD_5 (mg/l)	39.3
COD (mg/l)	136.0
BOD_5/COD	0.29
Ca (mg/l)	375
Pb (mg/l)	0.02
Cu (mg/l)	0.17
Mn (mg/l)	29.0
Zn (mg/l)	5.0
Cr (mg/l)	0.05
Ni (mg/l)	0.36
Na (mg/l)	33.0
Mg (mg/l)	113.0
K (mg/l)	120
Fe (mg/l)	80
Cd (mg/l)	0.02

4.2 Compaction Characteristics

The relationship between w_{opt} and MK content are illustrated in Fig. 2. As illustrated, the moisture content of laterite - MK mixtures decreased markedly with increase in the percentage of MK. The increase in moisture content with increasing MK concentration is clear evidence that MK requires a little amount of water for pozzolanic reaction with the silt and clay fractions of the soil. Fig. 3 shows the relationship between ρ_{dmax} and MK content. It could be observed from Fig. 3 that ρ_{dmax} increased markedly with increasing concentration of MK as well as increase in the compaction energy. The presence of high proportion of silicon oxide (SiO_2) and iron oxide (Fe_2O_3) in MK may in part be responsible for the production of heavier agglomerate particles which resulted in improvement of the mechanical properties of the compacted laterite - MK mixtures. The improvement in ρ_{dmax} of the compacted laterite - MK mixtures are somewhat consistent with the results of previous studies conducted on soilcrete specimens prepared with metakaolin (Kolovos, 2013) and peat modified with mineral mixture (Muhammad *et al.*, 2012). The authors attributed the improvement in ρ_{dmax} to reduction in pore spaces of the blends which resulted in formation of closely compacted soil matrix.

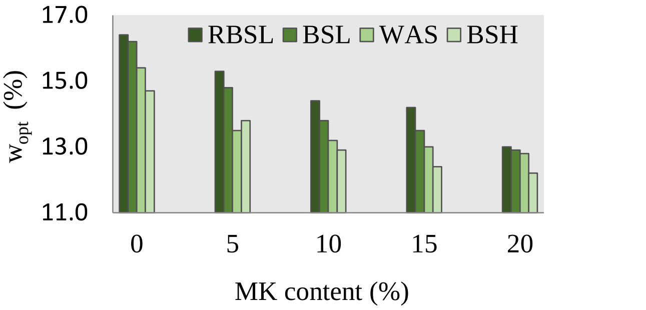

Fig. 2: Relationship between optimum moisture and MK content

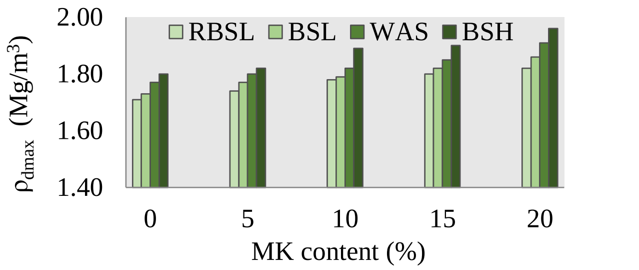

Fig. 3. Relationship between maximum dry density and MK content

4.3 Hydraulic Conductivity

The relationship between hydraulic conductivity and MK contents for deionized water and MSWL permeation are shown in Fig. 4. As may be seen from the results, the trends in the hydraulic conductivity are those of decreasing hydraulic conductivity with increase in percentage addition of MK. In general, hydraulic conductivities of compacted laterite - MK mixtures are lower than those of the compacted soil tested with no addition of MK. Similarly, hydraulic conductivity also decreases with increase in compaction energy. The results obtained in this study are consistent with those reported by several research groups for treated lateritic soil and black cotton soil (Yeheyis *et al.*, 2010; Etim, 2015; Oluremi, 2015; Umar *et al.*, 2016).

As illustrated in Fig. 4 (a), compacted laterite - MK mixtures permeated with deionized water yielded higher hydraulic conductivities ranging from 2.2 x 10^{-10} - 9.0 x 10^{-8} m/s. However, when the permeant was switched to MSWL, the hydraulic conductivity reduced markedly and ranged from 3.6 x 10^{-11} - 4.1 x 10^{-8} m/s (see Fig. 4b). Low hydraulic conductivity values obtained when MSWL was used as the permeant was due to biochemical reactions between the soil, MK and MSWL which resulted in the formation of new minerals. The results obtained in this study are consistent with the results reported by Umar *et al.* (2016) for compacted soil treated with iron ore tailings. The authors attributed the behavior of the iron ore tailings - soil mixtures to buildup of biomass from bacteria and yeast present in the MSWL which impedes the transport of fluid into the compacted soil matrix. Yeheyis *et al.* (2010) reported similar behavior for compacted soil treated with coal fly ash powder. The authors concluded that decrease in hydraulic conductivity of compacted soil - fly ash mixture was caused by the chemical interactions between acid mine drainage and fly ash which accelerated the development of new minerals. In general, the hydraulic conductivity of fine-grained soils majorly depends on (1) the availability of pore spaces within the soil, (2) the surface charge density of the soil and (3) the chemical nature of the waste in the landfill (Harrop-Williams, 1985; Stern & Shackelford, 1998). Apart from the influence of increase in compaction energy on hydraulic conductivity, the chemical nature of the permeant fluid also affects hydraulic conductivity.

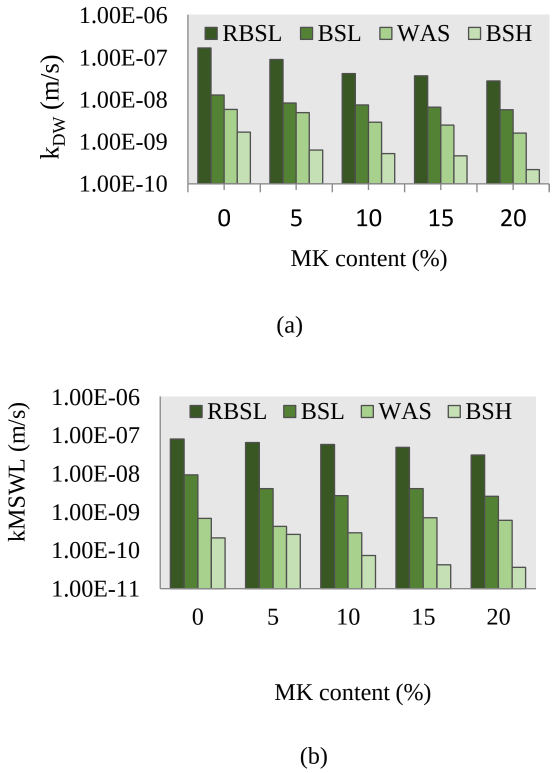

Fig. 4: Relationships between hydraulic conductivity and MK content (a) DW as permeant (b) MSWL as permeant

4.4 Statistical Analyses

Statistical analyses of the hydraulic conductivity results were carried out using the MINITAB 16.1 software for the various compactive efforts. A variety of studies have assumed that hydraulic conductivity of compacted soil is log-normally distributed (Freeze, 1975; Borgadi *et al.*, 1989). The regression equation can be represented as

$$\text{Lnk} = A - BL - CE \tag{2}$$

Where:

Lnk = Natural logarithm of hydraulic conductivity,
A = Overall mean effect
B, C = Constants
L = Metakaolin content (%),
E = Compactive effort

Equation 2 suggests that hydraulic conductivity of the treated soil decreased with increasing compaction energy as well as increase in percentage addition of MK.

Table 5. Two - way ANOVA table for the hydraulic conductivity models

Equation	Constants			Statistical parameters					
	A	B	C	F	F_{cr}	S	R^2	R^2 (adj)	P	Comment
ln k_{DW}	-13.94	-0.47	-1.53	107.35	3.59	0.56	0.93	0.92	0.000	Significant
ln k_{MSWL}	-14.40	-0.24	-2.04	237.68	3.59	0.47	0.97	0.96	0.000	Significant

4.5 Sensitivity Analysis

To evaluate the relative effect of MK and compactive effort on hydraulic conductivity of the treated soil, 5 % level of significance was used for the statistical analysis. The two - way analysis of variance (ANOVA) results for the models are summarized in Table 5. As it can be seen from Table 5, the calculated F - statistics for ln k_{DW} and ln k_{MSWL} are 107.35 and 237.68, respectively. These values are statistically significant at 5 % level of significance as they exceeded F critical (F_{cr}) value of 3.59. The results indicate that the relative effect of MSW leachate on hydraulic conductivity is more pronounced as the model yielded the highest calculated F-statistics value of 237.68. Furthermore, the regression statistics show that the effects of MK and compactive efforts on hydraulic conductivity are statistically significant as the probability values (p - values) are less than 0.05 in each case.

The regression equation developed based on permeation of the laterite - MK mixtures yielded low coefficient of determination (R^2) of 0.93 and high standard deviation (S) of 0.56. In contrast, the regression model developed base on permeation of the laterite - MK mixtures with MSWL exhibited low S value of 0.473 and high R^2 value of 0.97. A comparison of the statistical parameters summarized in Table 4 further suggest that compacted laterite - MK permeated with MSWL can be taken to give the best estimation of hydraulic conductivity. Moreover, the models clearly demonstrate that hydraulic conductivity of the compacted laterite - MK mixtures are sensitive to the type of permeant fluid used. Stern and Shackelford (1998) reported similar results for sand - processed clay mixtures permeated with calcium chloride solution.

4.6 Validation of the Models

The relationship between the predicted and measured values of hydraulic conductivity of the compacted MK - soil mixtures permeated with DW and MSWL, respectively are shown in Figs. 5 and 6. The results demonstrate that measured hydraulic conductivity correlates very well with the estimated or calculated values. The R^2 values obtained for the developed regression equations using the laboratory hydraulic conductivity results (See Table 4) are in reasonable agreement with the R^2 values depicted in Figs. 4 and 5 for the two permeant fluids. The developed regression model with MSWL as the permeant fluid (ln k_{MSWL}) is therefore adjudged suitable for predicting the hydraulic conductivity of compacted soils to be used as compacted liner for containment of MSW. However, the optimum compactive effort and optimum percentage of MK by weight of the soil required to achieve the design hydraulic conductivity of 1 x 10^{-9} m/s must also be established.

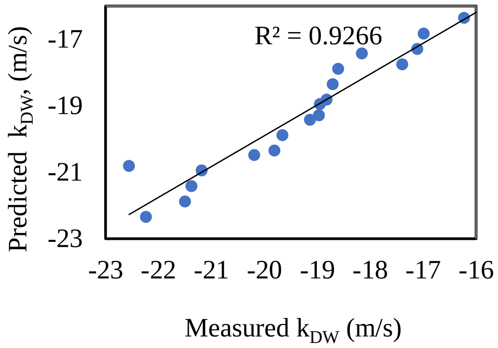

Fig. 5: Relationship between predicted and measured values of hydraulic conductivity of laterite - MK mixtures permeated with DW.

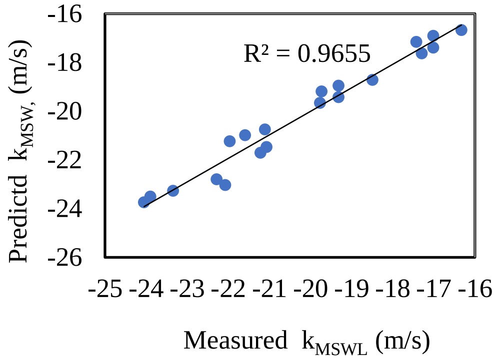

Fig. 6: Relationship between predicted and measured values of hydraulic conductivity of laterite - MK mixtures permeated with MSWL.

5 Conclusion

The study evaluated potentials of MK as treatment material for soil intended to be used as a liner material in hydraulic barrier system for containment of MSW. The compacted laterite - MK mixtures were permeated with DW and MSWL, respectively. Permeation of the treated soil with MSWL resulted in low values of hydraulic conductivity in comparison with DW permeation. From the viewpoint of economy and sustainability, soil treated with 5 % MK and compacted at the WAS energy level is adjudged suitable for use as liner material provided the compaction water content is maintained at 14.1 %.

Statistical analyses of the experimental results indicate that hydraulic conductivity (k), metakaolin content (MK) and compactive effort (E) are statistically significant at 5 % level of significance. Calculated F - statistics are significant at 5 % level of significance as the values exceeded Fcr value of 3.59. The regression models can therefore be used to define minimum MK content and compaction energy to achieve the maximum regulatory hydraulic conductivity of less than or equal to 1 x 10^{-9} m/s recommended for liners in hydraulic barrier system. Measured values of hydraulic conductivity were compared and found to exhibit good agreement with the predicted values.

REFERENCES

AASHTO M145-12 (2012). *Standard Specifications for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes,* American Association of State Highway and Transportation Officials, Washington, Wash, USA.

Amokrane, A., Comel, C. & Venon, J. K. (1997). Lanfill leachates pretreatment by coagulation – flocculation. *Journal of Water Research*. 31, 2775 – 2782.

ASTM D5084-10 (2008). *Standard Test Methods for Measurement of Saturated Porous Materials Using Flexible Wall Permeameter,* ASTM International, West Conshohocken, Pa, USA.

ASTM D2478-11 (2011). *Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System),* ASTM International, West Conshohocken, Pa, USA.

ASTM D698-12 (2012), *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft³ (600 kN-m/m³)),* ASTM International, West Conshohocken, Pa, USA.

ASTM C618-15 (2015). *Standard Specification for Coal Fly Ash and Raw Calcined Natural Pozzolan for use in Concrete*, ASTM International, West Conshohocken, Pa, USA.

Bhalla, B., Saini, M. S. & Jha, M. K. (2013). Effect of age and seasonal variations on leachate characteristics of municipal solid waste landfill. *International Journal of Research in Engineering and Technology.* 2 (8), 223 - 232.

Borgadi, I., Kelly, W. E., & Bardossy, A. (1989), Reliability model for soil liners: initial design, *Journal of Geotechnical and Geoenvironmental Engineering, 115*(5), 658-669.

Bradshaw, W., Connelly, E. F., Cook, M. F., Goldstein, J., & Pauly, J. (2005) *The Costs & Benefits of Green Affordable Housing*, New Ecology Inc.

BS 1377 (1990). *Methods of Testing Soils for Civil Engineering Purpose,* British Standard Institution, London.

Dinar, P., Sahoo, P. K., & Sriram, G. (2013), Effect of metakaolin on the properties of high strength concrete, *International Journal of Structures and Materials*, *7*(3), 215-223.

Etim, R. K. (2015). *Stabilization of Black Cotton Soil with Lime-iron Ore Tailing Blends,* Unpublished doctoral dissertation, Ahmadu Bello University, Zaria.

Freeze, R. A. (1989). Astochastic-conceptual analysis of one-dimensional groundwater flow in non-uniform homogeneous media, *Water Resource Research*, *11*(1975), 725-741.

Hamdi, N., & Srasra, E. (2013), Hydraulic conductivity of compacted clay soils used as landfill liners for an acid waste, *Waste Management*, *33*(1), 60-66.

Harrop-Williams, K. (1985), Clay liner permeability: evaluation and variation, *Journal of Geotechnical Engineering*, *111*(10), 1211-1225.

Ilić, B. R., Mitrović, A. A., & Miličić, L. R. (2010), Thermal treatment of kaolin clay to obtain metakaolin, *HemijskaIndustrija*, *64*(4), 351-356.

Kula, I., Olgun, A., Senvinc, V., & Erdogan, Y. (2002), An investigation on the use of tincal ore waste, fly ash and coal bottom ash as Portland cement replacement materials, *Cement and Concrete Research*, *32*(2), 227-232.

Kleppe, J., & Oslon, R. (1995), Desiccation Cracking of Soil Barriers, *Hydraulic Barriers in Soil and Rock*, STP 874, ASTM, Philadelphia, Pa, USA, 263-275.

Kolovos, K. G., Asteris, P. G., Cotsovos, D. M. Badogiannis, E., & Tsvilis, S. (2013) Mechanical properties of soilcrete mixtures modified with metakaolin, *Construction and Building Materials*, *47*, 1026-1036.

Mitchell, J. K. (1993). *Fundamentals of Soil Behavior,* New York,Wiley and Sons.

Modarres, A., & Nosoudy, Y. M. (2015), Clay stabilization using coal waste and lime-technical and environmental impact, *Applied Clay Science, 116*, 281-288.

Muhammad, N., Namdar, A., & Zakaria I. B. (2012) Improving peat engineering properties by natural mineral mixture, International Journal of Civil Engineering and Geo-environment *3*, 23-27.

Oluremi, J. R. (2015). *Evaluation of Waste Wood Ash Treated Lateritic Soil for use in Municipal Solid Waste Containment Application.* Unpublished doctoral dissertation, Ahmadu Bello University, Zaria.

Osinubi, K. J., & Eberemu, A. O. (2009), Compatibility and attenuative properties of blast furnace slag treated laterite, *The Journal of Solid Waste Technology and Management*, *35*(1) 7-12.

Ramesh, H. N., Krishna, A. J., & Supriya, M. D. (2012), Effect of lime on compaction and strength of red earth treated with mine tailings, *Journal of Mechanical and Civil Engineering,* 2(4), 1-6.

Roy, T. K. (2013). Evaluation of clayey soil by UCS with the addition of rice husk ash and lime in: *Proceedings of the 7th International Conference on Case Histories in Geotechnical Engineering,* Chicago, IL, USA, *2013,* 1-5.

Stern, R. T., & Shackelford, C. D. (1998), Permeation of sand-processed clay mixtures with calcium chloride solution, *Journal of Geotechnical and Geoenvironmental Engineering, 124*(3), 231-241.

Umar, S.Y., Elinwa, A. U., & Matawal, D. S. (2015), Feasibility of using tincal ore waste as barrier material for solid waste containment, *Journal of Mechanical and Civil Engineering*, *12*(1), 1-10.

Umar, S. Y., Matawal, D. S., & Elinwa, A. U. (2016), Hydraulic conductivity of compacted laterite treated with iron ore tailings, *Advances in Civil Engineering*, *2016*, 1- 8.

US EPA (1989). *Requirements for Hazardous Waste Landfills, Design, Construction and Closure,* Tech. Rep. EPA-125/4-89. 022, EPA, Cincinnati, Ohio, USA.

Yeheyis, M. B., Shang, J. Q., & Yanful, E. K. (2010), Feasibility of using coal fly ash for mine waste containment, *Journal of Environmental Engineering 136*(7), 682-690.